A Cost-Effective Hybrid Capacitive-Camera Eye Tracker for Diagnosing Neurodegenerative Diseases

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Introduction

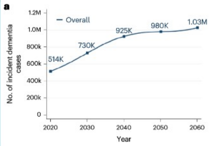

Figure 1: Estimated number of US adults who will develop dementia each year from 2020 to 2060
Source: https://www.nature.com/articles/s41591-024-03340-9

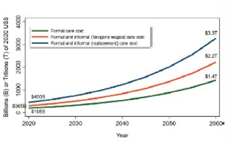

Figure 2: Projected cost of Alzheimer's disease and related dementias formal and informal care in the US, 2020 to 2060.
Source: https://www.nature.com/articles/s41514-024-00136-6

- Neurological conditions can greatly affect a patient's quality of life and pose significant challenges for healthcare systems
- **Early diagnosis** can lead to more effective treatments and better results for patients
- Existing screening tests suffer from biases that prevent objective measurements of the patient's cognitive performance
- Eye tracking is a technology that has the potential to offer non-invasive objective measurements of a patient's neurological health through **analysis of eye movements**.
- Most eye tracking devices are video-based, which means that they use cameras to record eye movements. However, to record high-speed eye movements, cameras are not practical, as high-speed cameras are **very costly and inaccessible**.

Existing Solutions

	60 fps Camera Eye Tracker	1000 fps Camera Eye Tracker	1000hz Capacitive-Camera Eye Tracker
Cost	~$50	~$1000	~$80
Refresh Rate	60hz	1000fps	1000hz
Precision	~0.1 degrees	~0.1 degrees	~0.1 degrees

Table 1: Comparison of different eye tracking techniques.
Prices estimated from cost of components only

- For clinical use, the eye tracking device must meet the **required** specifications to accurately track eye movements. These specifications are at least 0.1 degrees of precision and a 1000hz refresh rate.
- Camera-based eye trackers that use consumer grade cameras are affordable, but cannot meet the required refresh rate.
- Eye trackers that used specialized high speed cameras can meet the required refresh rate, but are significantly more expensive, with the cheapest devices costing over a **$1000**.
- The hybrid device designed in this study meets the required specifications while only costing **$80** in components. The cost is much less due to the fusion of a cheap camera-based eye tracker with capacitive sensors that can provide high refresh rates.

Objectives

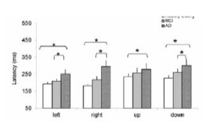

Figure 3: Saccade Latency compared in adults with AD, MCI, and a healthy control population.
Source: https://pmc.ncbi.nlm.nih.gov/articles/PMC3705110/

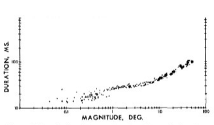

Figure 4: Saccade duration as a function of magnitude of travel
Source: https://www.sciencedirect.com/science/article/abs/pii/002555

- **1000hz refresh rate:** Saccades, which are rapid darting movements of the eye, need to be accurately recorded to gain insights into a person's neurological health. The smallest saccades only last for 25ms, so a 1kHz refresh rate is needed to accurately record their properties.
- **0.1 degrees of precision:** The smallest saccades induce 1 degree of eye rotation, so 0.1 degrees of precision is required to accurately track saccadic motion.
- **Less than $100 in cost:** Eye tracking technology is most needed in communities that don't have access to medical professionals and brain imaging machines, so to maximize accessibility, cost must be kept at a minimum.

Proposal

- The study aims to develop a **hybrid capacitive-camera eye tracker** that meets the performance specifications required for clinical use as a tool to diagnose neurodegenerative disease.
- The proposed device will combine data from a low cost camera recording at 30fps with capacitive sensors that record at 1000hz.
- A **hybrid algorithm** will be developed to combine both data streams while compensating for drifts in the reading or occlusions.
- By combining the spatial resolution of a low-cost camera with the temporal resolution of capacitive sensors, the hybrid device will **approximate the same eye tracking performance** as a regular high speed camera, but at a lower cost.

Methodology

FEM Simulation

- To simulate the precision of the capacitance sensing system, a **finite element method** (FEM) electromagnetic field simulation was conducted.
- The eyeball was modeled as a sphere with a radius of 12mm and the sensor as a square with a side length of 20mm.
- A 12.88fF change was simulated, correlating to a precision of **0.93 degrees**.

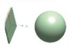

Figure 5: Model of the simulation setup created in Ansys Maxwell

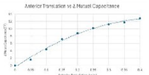

Figure 6: Simulated capacitance as a function of eye translation. Figure created using Excel from data collected using Ansys Maxwell

Sensor Fabrication

- **Laser-Induced Graphene** (LIG) was chosen to create sensitive capacitive sensors because of its high electrical conductivity and surface area
- Polyimide film was heated up using a CO_2 laser to create the graphene sensor.

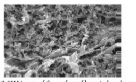

Figure 7: SEM image of the surface of laser-induced graphene Source: https://www.researchgate.net/figure/SEM-image-of-the-surface-of-laser-induced-graphene_fig2_342196011

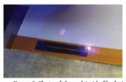

Figure 8: Photo of the polyimide film being heated using a desktop laser engraver.

Pupil Identification

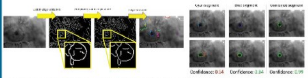

Figure 9: Steps of the PuRe algorithm (left to right), input image, canny edge detection, edges after manipulation, selected edge segments, confidence score of the 3 best segments, including a combined segment. Images taken from (Santini et al., 2018).

- To track the eye movements in the camera frame, the PuRe pupil identification algorithm was implemented.
- The algorithm uses an **edge selection algorithm** to identify the elliptical pupil in the camera frame. The algorithm also outputs a **confidence score** for the identified pupil.

Figure 10: Example images taken from the device's camera. Left shows an image with a high confidence score of 1.0. Right shows an image with a low confidence score of 0.72.

Hybrid Algorithm

- The hybrid algorithm fuses **30hz** data from the camera with **1000hz** data from the capacitive sensor to output a single gaze prediction. The algorithm runs once every millisecond and works as follows:
  - If a new camera frame is available and the confidence score is above a set threshold, use only the camera frame to make the gaze prediction.
  - If a new camera frame is not available, take the change in pupil location measured by the capacitive sensors and add it onto the last obtained pupil location from the camera.

$$P(t) = F(t_0) + C(t) - C(t_0)$$

Figure 11: The equation for the hybrid algorithm, where P(t) is the gaze prediction at any time t, t_0 is the time of the last available camera frame, $F(t_0)$ is the gaze prediction from the last available camera frame, and $C(t) - C(t_0)$ is the change in gaze prediction measured by the capacitance sensor from time t to t_0.

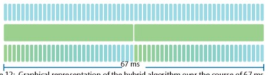

Figure 12: Graphical representation of the hybrid algorithm over the course of 67 ms. Top blue bars represent each capacitance measurement. Middle green bars represent each camera frame. Bottom represents the output gaze prediction as a hybrid of the two.

Frame Construction

- The first iteration of the device used a 3D printed pair of glasses as the base of the device. The frame was lightweight and easy to construct, but could not adjust to different face shapes, and could shift around, leading to **inaccurate tracking**.

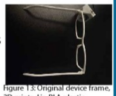

Figure 13: Original device frame, 3D printed in PLA plastic

- The second iteration of the device used the frame of an old VR headset. The frame provided foam padding and an adjustable size, allowing for a tight but comfortable fit on the user's head.
- A single 10ft USB 3.0 cable was used for all data communication, with the camera and arduino microcontroller connected through a USB hub. The capacitive sensor was placed in a plastic enclosure to minimize **parasitic capacitance**.

Figure 14: Second iteration of device frame, using an adjustable head strap

Software Integration

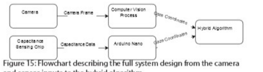

Figure 15: Flowchart describing the full system design from the camera and sensor inputs to the hybrid algorithm

- Two separate computers were used to implement the hybrid device. An **Arduino microcontroller** was used to read the capacitance measurements from the sensor chip and send the data over serial to an external laptop. The camera directly sent the recorded image frames to the laptop.
- On the laptop, two separate processes were ran at once. One process ran the **pupil identification algorithm**, while the other process ran the **hybrid algorithm**, outputting the final gaze prediction.

Prototype Validation

Research Trial

- To measure the performance of the device, a research trial was conducted with **10 volunteers** (ages 16-60).
- The trial was set up on a table with a monitor for displaying the stimulus.
- The trials began with a calibration screen, and then 3 tests were conducted to measure different eye metrics.

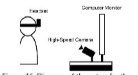

Figure 16: Diagram of the setup for the research trial, including the hybrid device, high speed camera, and computer monitor.

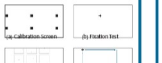

Figure 17: Eye stimulus screens displayed on the computer monitor during the trial

Benchmark Comparison

- During the research trial, a **high speed camera** was also recording the volunteer's eye movements. The high speed camera provided a benchmark to compare to the hybrid device.
- By comparing the recorded eye metrics from both devices, the validity of the hybrid device as a true replacement for high-speed camera eye trackers can be tested.
- The high speed camera was mounted to the table during the trial and recorded at **1000 fps**.

Figure 18: High speed camera used during trial (Basler Ace acA640-750um). Zoom lens attached to record only the eye movements. Recorded video at 1000fps. over ethernet.

Data Analysis

Cross-Sensor Calibration

- To allow for merging of the two sensor readings, a calibration procedure was conducted at the beginning of the trial. A **third-order polynomial regression model** was then fitted to establish a transformation function that converts raw capacitive sensor data into pupil coordinates that align with the camera's output.

Confidence-Based Filtering

- The pupil detection algorithm assigns a confidence score between 0.0 and 1.0 to each detected pupil location.
- Calibration points where the confidence score was below 0.95 were **discarded** to prevent inaccurate data from affecting the model

Performance Specifications

- The difference between the true eye position and measured eye position was used to calculate the error. The error was averaged across all recorded points to find the average accuracy.
- To calculate the precision of the device, the **root mean square** (RMS) of the angular distance between every recorded point during the fixation test was measured.
- For each recorded eye metric, the values were calculated using the technique established by (Pavisic et al., 2017).

Results

Specification	Horizontal (degrees)	Vertical (degrees)
Accuracy	0.5439 (0.2940)	0.6670 (0.4673)
Precision (RMS)	0.0812 (0.0345)	0.0889 (0.0395)

Table 2: Eye tracker specifications, where accuracy and precision are given in degrees, and the refresh rate is measured in hertz. The numbers in parenthesis are the standard deviations

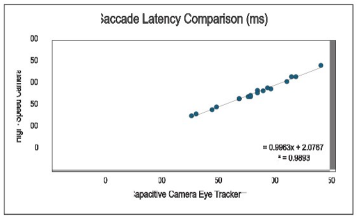

Figure 19: Saccade latency as measured by the hybrid device and the high speed camera. Graph created in Excel using data from the research trial.

	Camera-Capacitive Eye Tracker	High Speed Camera	Percent Difference
Maximum fixation (ms)	2,807	2,821	-0.4963%
Number of Saccades	1.81	1.88	-3.7234%
Time to reach Target (ms)	298	302	-1.3245%
Pursuit gain	1.43	1.42	0.7042%

Table 3: Comparison of 4 different eye metrics as recorded by the hybrid device and the high speed camera, as well as the percent difference.

Discussion

92% Reduction in Cost

< 4% Deviation

Figure 20: Important findings from the study. Price reduction is compared to a $1000 high speed camera, taken as a low-end estimate. <4% Deviation compared to a traditional high speed camera in all recorded metrics

- The precision and accuracy values are within the required ranges for tracking saccades, validating the potential of the device to serve as a tool for screening and diagnosing neurodegenerative diseases.
- There was a measurable difference in accuracy and precision between vertical and horizontal movements, mainly due to eyelashes and eye lids making the pupil difficult to locate when the pupil moves vertically. Adding **additional cameras** at different angles could help resolve this issue.
- These results indicate that the hybrid device can serve as a **low-cost replacement** for expensive high-speed eye trackers without sacrificing performance.

Implementation

- A windows app was created to allow users to control the device without needing to download code. The app included a control panel for the user and a seperate screen where the stimulus is displayed. The app allows users to save the results from the test and then share with medical professionals over the internet, allowing for remote diagnosis.

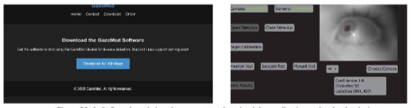

Figure 21: (Left) Sample website where users can download the application and order the device. (Right) Application screen, including controls to run the device and view of camera feed.

- To allow the device to be easily manufactured and distributed, a fully 3D-printed version of the headset was designed. The design featured the same adjustable headstrap, but allowed for mass-manufacturing of the frame.

Figure 22: Render of 3D Printed Frame

Conclusion

Summary of Findings

- By leveraging the **high spatial resolution** of cameras with the **high temporal resolution** of capacitive sensors, the developed hybrid eye tracker provides high speed eye tracking at a lower cost.
- In testing, the device measured eye metrics within **4%** of the values recorded by a high speed camera, but with a **92%** reduction in cost.

Significance

- Eye trackers have the potential to offer **objective non-invasive measurements** of a patient's neurological health, offering a significant advantage over traditional paper tests that can introduce biases and inconsistencies due to the need for a human examiner. The low cost of the hybrid device improves the accessibility of the technology.

Future Work

- The next steps for the device include running **clinical trials**, where patients with neurodegenerative disease are tested using the hybrid device and the results are then compared to traditional cognitive tests.